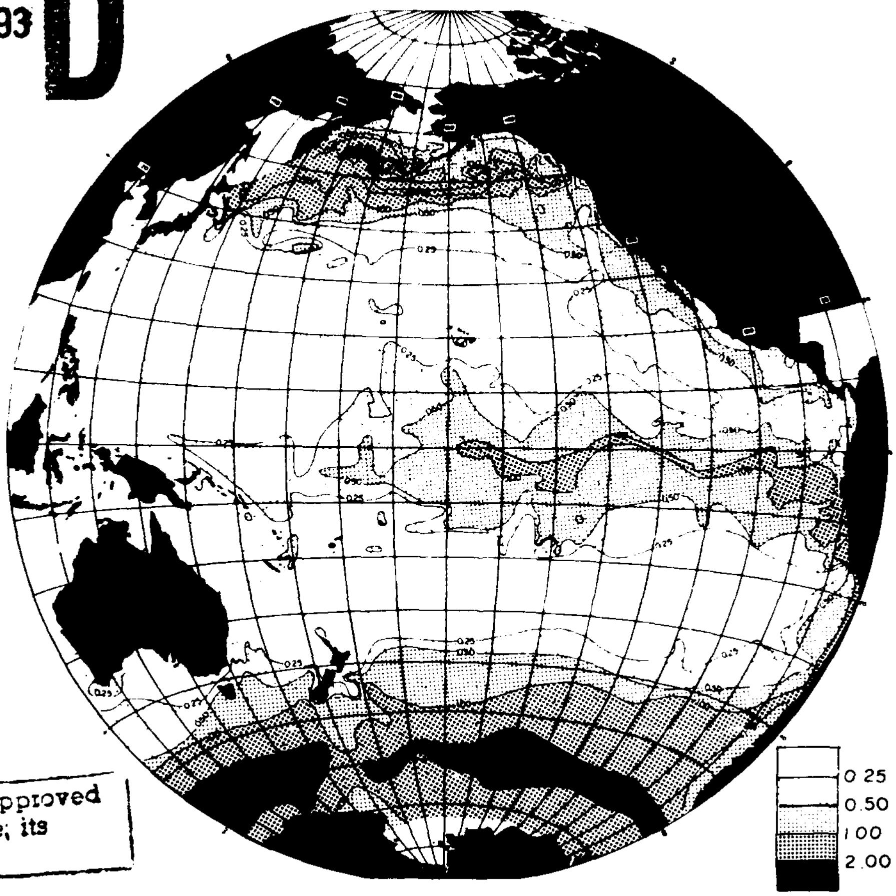
REPORT

AMERICAN SOCIETY OF LIMNOLOGY AND OCEANOGRAPHY SYMPOSIUM

WHAT CONTROLS PHYTOPLANKTON PRODUCTION IN NUTRIENT-RICH AREAS OF THE OPEN SEA?

February 22-24, 1991
San Marcos, California



Distribution of inorganic phosphate-phosphorus (µg-at/l) at the surface of the Pacific Ocean (Reid, J.L., 1962).

Supported by

U.S. Environmental Protection Agency
U.S. Office of Naval Research
U.S. Department of Energy
U.S. National Aeronautics and Space Administration
U.S. National Science Foundation

AMERICAN SOCIETY OF LIMNOLOGY AND OCEANOGRAPHY

SYMPOSIUM REPORT:

WHAT CONTROLS PHYTOPLANKTON PRODUCTION IN NUTRIENT-RICH AREAS OF THE OPEN SEA?

February 22-24, 1991
San Marcos, California

The figure on the front cover first appeared in Reid, J.L., 1962. On the circulation, the phosphate-phosphorus content, and the zooplankton volumes in the upper part of the Pacific Ocean. *Limnol. Oceanogr.* 7(3): 287-306.

Printed on recycled paper

ACKNOWLEDGEMENTS

The symposium on "What Controls Phytoplankton Production in Nutrient-Rich Areas of the Open Sea?" was organized by the American Society of Limnology and Oceanography, through a Program Steering Committee composed of **Sallie W. Chisholm** (Co-Chair), Massachusetts Institute of Technology; **John J. Cullen** (Co-Chair), Bigelow Laboratory for Ocean Sciences; **Karl Banse**, University of Washington; **Bruce W. Frost**, University of Washington; **John H. Martin**, Moss Landing Marine Laboratory; **Diane M. McKnight**, United States Geological Survey; **Trevor Platt** (ex officio), Bedford Institute of Oceanography; and **C. Susan Weiler** (ex officio), Whitman College.

The consensus statement was developed by **Sallie W. Chisholm**, Massachusetts Institute of Technology; **John J. Cullen**, Bigelow Laboratory for Ocean Sciences; **Richard T. Barber**, Duke University; **Ann E. Gargett**, Institute of Ocean Sciences, Sidney; **John T. Lehman**, University of Michigan; **James J. McCarthy**, Harvard University; **James J. Morgan**, California Institute of Technology; **Barbara B. Prézelin**, University of California, Santa Barbara; **William G. Sunda**, U.S. Office of Naval Research; and **T. David Waite**, Australian Nuclear Science & Technology Organization.

This report was compiled by C. Susan Weiler, June 25, 1991.

The symposium and resulting publications would not have been possible without the early expression of interest and encouragement provided by Henry A. Walker of the U.S. Environmental Protection Agency's Environmental Research Laboratory in Narragansett, Rhode Island.

Primary support for the symposium, symposium report, and symposium issue of *Limnology and Oceanography* (in prep.) was provided by: the U.S. Environmental Protection Agency's Global Change Research Program and the U.S. Department of Navy's Office of Naval Research's Ocean Chemistry Program (ONR grant N00014-91-J-1506); the U.S. Department of Energy (DOE grant DE-FG06-91ER61160); the U.S. National Aeronautics and Space Administration's Ocean Biogeochemistry Program; and the U.S. National Science Foundation's Ocean Sciences Division and Division of Polar Programs. The support does not constitute an endorsement by any supporting agency of the views expressed in this document.

Additional copies may be obtained from:

American Society of Limnology & Oceanography
Dr. C. Susan Weiler, Executive Director
Department of Biology
Whitman College
Walla Walla, WA 99362
USA

TABLE OF CONTENTS

INTRODUCTION

The oceans play a critical role in regulating the global carbon cycle. Deep-ocean waters are roughly 200% supersaturated with CO_2 compared to surface waters, which are in contact with the atmosphere. This difference is due to the flux of photosynthetically derived organic material from surface to deep waters and its subsequent remineralization, i.e. the "biological pump". The pump is a complex phytoplankton-based ecosystem. It is driven by sunlight, and fueled by the supply of inorganic nutrients derived primarily from the deep ocean. In areas of the oceans where inorganic N and P are effectively exhausted by phytoplankton in surface waters during the growing season, the pump functions at maximal efficiency: The transport of carbon to depth is limited by the flux of N and P into the surface waters. In the Southern Ocean, near the equator, and in the subarctic Pacific, however, relatively high concentrations of nitrate and phosphate are found in the surface waters throughout the year, and phytoplankton biomass and net production are much lower than would be expected based on the availability of major nutrients. Thus in these areas of the oceans the biological pump appears to be operating at less than maximal efficiency. Consequently, these regions are receiving increased attention, not only as they relate to global biogeochemical cycles, but also as potential sites for anthropogenic enhancement of CO_2 flux into the ocean.

The paradoxical nature of ocean regions containing high nutrients and low phytoplankton populations has intrigued biological oceanographers for many years. Hypotheses to explain the paradox include the regulation of productivity by light, temperature, zooplankton grazing, and trace metal limitation and/or toxicity. To date, none of the hypotheses, or combinations thereof, has emerged as a widely accepted explanation for why the nitrogen and phosphorus are not depleted in these regions of the oceans. Recently, new evidence has emerged which supports the hypothesis that iron limitation regulates primary production in these areas. This has stimulated discussions of the feasibility of fertilizing parts the Southern Ocean with iron, and thus sequestering additional atmospheric CO_2 in the deep oceans, where it would remain over the next few centuries. The economic, social, and ethical concerns surrounding such a proposition, along with the outstanding scientific issues, call for rigorous discussion and debate on the regulation of productivity in these regions.

To this end, The American Society of Limnology and Oceanography (ASLO) held a Special Symposium on the topic at the Lake San Marcos Resort and Conference Center on Feb. 22- 24th, 1991. A total of 145 individuals attended the full symposium, and another six were present for one day. Participants included leading authorities, from the U.S. and abroad, on physical, chemical, and biological oceanography, plant physiology, microbiology, and trace metal chemistry. Representatives from government agencies and industry were also present.

SYMPOSIUM SCOPE

The three-day symposium addressed the general question of the role of the "biological pump" in the global carbon cycle, and the regulation of the pump in areas of the oceans where N and P are in excess, i.e. the subarctic and equatorial Pacific, and the Southern Ocean. A physical, chemical, and biological characterization of these areas of the oceans was presented, along with existing uncertainties in the global carbon budget and the role of the biota in models of this budget. Changes in the global CO_2 cycle over geological time scales, and hypothesized causes for the changes, were analyzed to provide a perspective and foundation for discussion.

The evidence in support of the various hypotheses for the regulation of productivity in the N- and P-rich oceans was presented and discussed. Particular attention was given to the "iron hypothesis" because of the unique set of concerns surrounding it, but alternate hypotheses and interpretations were also addressed at length.

Much of the last day of the symposium was devoted to discussing the feasibility and advisability of fertilizing large regions of the Southern Ocean with iron with the hope of mitigating the increase of atmospheric CO_2 and associated climate change. It was assumed, for the sake of discussion, that iron fertilization would allow the phytoplankton to completely utilize the excess N and P in these regions. Model analyses which estimate the amount of carbon that could, in theory, be drawn out of the atmosphere as a result of fertilization were presented and discussed. The discussion explored the potential effects on the food web, the influence on other areas of the oceans and atmosphere, and the time scale of change. Our confidence in our ability to predict consequences of such intervention from our current understanding of the ecology of aquatic ecosystems was discussed, and recommendations for the future were formulated.

The following statement, which was drafted by a subset of symposium participants charged with the task, reflects the general outcome of the meeting.

CONSENSUS STATEMENT

Introduction

There is mounting concern over recent increases in concentrations of "greenhouse" gases in the Earth's atmosphere, and their potential consequences on global climate. Slowing the rate of increase of these gases will be difficult. Because of the multiple sources and complex fates of these compounds, a single significant solution to this problem is unlikely. Alternative technologies, such as the development and use of non-fossil fuel energy sources in developing and developed countries alike, should be pursued vigorously along with stringent conservation measures. Unfortunately, however, the time required to implement new technology, once developed, will be decades. Projections based upon current gas emissions, and trends in population growth and economic development, leave no doubt that all possible means of reducing the concentrations of greenhouse gases in the Earth's atmosphere must be given immediate and serious consideration. These include more efficient uses of

available energy, and enlightened management and stewardship of the natural sources and sinks for these compounds.

Potential Impact of Iron Fertilization

The oceans play a critical role in the global carbon cycle, and it has been suggested that regions of the ocean with an excess supply of nitrogen and phosphorus, such as the Southern Ocean, could be fertilized with iron to sequester atmospheric CO_2. Model calculations presently suggest that if iron fertilization of nutrient-rich seas succeeded in stimulating complete assimilation of nutrients, and was continued for the next 100 years, the buildup of CO_2 in the atmosphere (assuming the "business as usual" emissions scenario) could be reduced by 17 to 25% . We must consider, however, that the current generation of models may not have quantitative ability; they do not include a variety of important processes such as light limitation and zooplankton grazing, which could limit nutrient uptake long before nutrients are completely depleted.

Moreover, little if anything is known about the potential adverse effects such fertilization would have on marine ecosystem structure and function. For example, recent experiments have shown that iron enrichments to plankton communities enclosed in bottles can cause dramatic changes in phyto-plankton species composition. If these types of changes were triggered on a larger scale, they would propagate through the food web causing major changes at the higher trophic levels. In addition, model simulations reveal the potential for other large-scale consequences of fertilization. The fertility of other regions of the worlds oceans could be diminished if nutrients presently being supplied have been redistributed. The stimulation of production would also accelerate the nitrogen cycle, possibly increasing nitrous oxide release into the atmosphere. Moreover, large regions of the deep ocean could become anoxic as a result of increased productivity in the Southern Ocean. Deep-ocean anoxia would stimulate the production of methane which, like nitrous oxide, is a much more powerful greenhouse gas than CO_2.

Evidence for Iron Limitation of Nutrient-Rich Seas

Thus, based upon our current understanding of the regulation of productivity in nutrient-rich seas, we believe that massive iron fertilization of the Southern Ocean to mitigate greenhouse warming is unwarranted; the potential gains are small relative to unknown, perhaps large, risks. Nevertheless, a majority of the scientists assembled by ASLO to discuss this issue are convinced that sufficient evidence exists in support of the hypothesis that iron plays an important role in regulating the productivity and trophic structure of planktonic communities to warrant increased efforts to explore this hypothesis.

The evidence is as follows:

◆ All of the high-nutrient low chlorophyll areas of the oceans are regions with low eolian inputs of iron.

◆ Data from the Vostoc ice cores reveal that during glacial times, when atmospheric CO_2 concentrations were lower than at present, the iron-rich atmospheric dust loads were 50 times higher than

during past and present interglacial periods, which suggests that this "natural" fertilization with iron might have resulted in increased phytoplankton production and consequent reduction in atmospheric CO_2.

◆ Addition of small amounts of iron to plankton communities enclosed in bottles stimulates the net rate of particulate chlorophyll, carbon, and nitrogen production and in addition, changes the phytoplankton community composition. We note, however, that the magnitude of biomass increase might not be achieved in the presence of the large grazers, which are *de facto* excluded from such bottle experiments.

◆ Iron additions have been shown to cause a shift in the nitrogen utilization patterns of the phytoplankton from ammonium to nitrate, presumably because iron is required for nitrate reduction.

◆ Marine algal species exhibit wide differences in their growth requirements for iron, which closely match the differences in iron levels in the waters from which the species were isolated. This suggests that iron availability is an important agent of natural selection in the oceans.

Although the collected evidence is compelling, it has not yet been demonstrated that iron enrichment stimulates the specific growth rate (as opposed to final yield) of phytoplankton species in bottle experiments. Moreover, we have no way of predicting, at present, whether iron enrichment in the presence of the entire food web would result in increased net community production (i.e. carbon that would ultimately be sequestered in the deep ocean). The first of these questions can be addressed through bottle experiments, because the answer is independent of grazing pressure. The second, however, could only be addressed through an unenclosed enrichment experiment in the ocean.

Recommendations for Future Research

Because iron is required in trace amounts by phytoplankton (C:Fe ratios in cultures range from 30,000 to 500,000) it is theoretically possible to carry out moderate-scale enrichment experiments with this element in areas of the oceans where it is hypothesized to limit plankton production. The power of this type of experimental manipulation of natural systems has been amply demonstrated by limnologists in their studies of the conditions that control productivity and food web dynamics in lakes.

Nutrient-rich seas that have very low *in situ* iron concentrations and very low rates of atmospheric iron input provide the perfect natural setting for such an experiment. The challenge, though, is not simply to demonstrate that iron limitation of phytoplankton production in these regions could be artificially alleviated, but to determine the implications of such increased productivity for carbon sequestration in the deep ocean. As described above, without a full study of the effect on planktonic food web dynamics, there is no assurance that an increase in productivity would result in a greater storage of carbon in the ocean.

It is important, therefore, that we examine this hypothesis in depth, and consider designing a modestly scaled iron-enrichment experiment in a high-nutrient region of the open sea. The scale of

the experiment must be both large enough to analyze planktonic food web dynamics, but small enough to avoid any long-term environmental impact. Such an experiment would not only yield insights into the role of iron in regulating productivity in these areas, but would also shed light on unresolved issues regarding the roles of light, macronutrients, and grazing pressure on regulating phytoplankton production in these and other marine ecosystems.

It was the view of the assembled group that several research directions should be pursued before implementation of an open-ocean iron-enrichment experiment would be justified. These include:

◆ Bottle experiments in which the specific growth rates of individual species of phytoplankton are measured in response to iron additions.

◆ Studies of iron-speciation chemistry in seawater, along with the chemical and photochemical processes that control that chemistry.

◆ Determination of the factors and mechanisms that regulate the acquisition of iron by marine plankton, including the possible role of siderophores in microbial iron uptake.

◆ Studies of the comparative physiology and biochemistry of iron utilization in phytoplankton isolated from coastal, oligotrophic, and nutrient-rich oceanic ecosystems.

◆ Development of physiological and biochemical indicators to diagnose the nutrient status of algal populations and communities *in situ*.

◆ Determination of the relative importance of eolian and *in situ* (e.g. upwelling) sources of iron to the euphotic zone in different oceanic regions, and examination of the relationship between iron supply and macronutrient utilization in the world's oceans.

◆ Studies of nutrient-rich oceanic regions that receive periodic eolian inputs of iron, or areas upstream and downstream of iron sources from sediments, to determine the response of planktonic communities to natural iron additions.

◆ Development of simulation models with more realistic biological components such as light limitation and food web dynamics.

Given recent projections, it is apparent that the buildup of greenhouse gases will continue well into the next century. The studies listed above will facilitate better predictions of the potential consequences of ocean manipulation. More importantly, they will fill critical gaps in our understanding of the role of the oceans in the global carbon cycle.

RESOLUTION
Ocean Fertilization and Atmospheric Carbon Dioxide

The following resolution was drafted by the symposium participants on Feb. 24, 1991, and adopted by the American Society of Limnology and Oceanography on June 9, 1991:

Recent research suggests that primary production in some nutrient-rich areas of the open sea may be limited by iron deficiency. This suggestion has stimulated discussion concerning the feasibility of fertilizing the Southern Ocean with iron as a means of reducing carbon dioxide concentrations in the atmosphere.

WHEREAS major manipulations of the Southern Ocean by iron fertilization is a scientifically uncertain mitigation measure to reduce rising carbon dioxide levels in the atmosphere; and

WHEREAS even if fully implemented and successful, this measure would likely at best postpone the impending climate change by a few years if not combined with significant reduction in carbon dioxide emissions;

THEREFORE BE IT RESOLVED that the American Society of Limnology and Oceanography *urges all governments* to regard the role of iron in marine productivity as an area for further research and not to consider iron fertilization as a policy option that significantly changes the need to reduce emissions of carbon dioxide.

SYMPOSIUM AGENDA

"What Controls Phytoplankton Production in Nutrient-Rich Areas of the Open Sea?"

Feb. 22-24, 1991, Lake San Marcos Conference Center
San Marcos, California

STEERING COMMITTEE: Sallie W. Chisholm and John J. Cullen, Co-Chairs; Karl Banse, Bruce Frost, John Martin, Diane McKnight, Claire Schelske, Trevor Platt (ex officio), and Susan Weiler (ex officio)

DAY 1, FRI, FEB. 22

Opening Statements
08:30 - 09:00

Processes and Hypotheses
09:00 - 12:00, Sallie W. Chisholm, Chair

Ann Gargett: Physical Processes and the Maintenance of Nutrient-Rich Euphotic Zones.

Alan R. Longhurst: Role of the Marine Biosphere in the Global Carbon Cycle.

John Cullen: Hypotheses to Explain High-Nutrient Low-Chlorophyll Conditions.

John Lehman: Bottom-Up vs Top-Down Control of Aquatic Food Webs: Lessons From Limnology.

Regulation of Phytoplankton Production
13:30 - 17:00, Theodore J. Smayda, Chair

Francois M. M. Morel: Micronutrient Utilization by Phytoplankton.

Paul Falkowski: Physiological Limitations and their Diagnosis.

John A. Raven: Inorganic Carbon Acquisition Mechanisms in Marine Phytoplankton and their Implications for the Use of Other Resources.

Bruce W. Frost: High Phytoplankton Production, High Nutrient Concentration and Low Phytoplankton Stock Implies Grazing Control.

Lawrence R. Pomeroy: Food Web Structure and Function: Potential Feedbacks to Phytoplankton.

Posters
17:30 - 19:15

DAY 2, SAT, FEB. 23

Regional Descriptions
08:30 - 10:00, James A. Yoder, Chair

Arnold L. Gordon: Antarctic Surface Water Renewal [cancelled].

Cornelius Sullivan: Antarctic Production, Patterns from CZCS Images [substituted for Gordon].

Charles B. Miller and Thomas M. Powell: If Nutrient-Rich Systems are Iron Limited, They are Adapted to it: the Subarctic Pacific Case.

Richard T. Barber: Regulation of Phytoplankton Production in the Nutrient-Rich Equatorial Pacific.

DAY 2, SAT, FEB. 23, continued

Iron

10:20 - 12:00, William G. Sunda, Chair

John H. Martin: The Case for Iron Limitation.

Robert A. Duce: The Atmospheric Transport of Iron and its Deposition in the Ocean.

Anita G. J. Buma: The Role of Iron and Manganese in Various Antarctic Plankton Communities.

Other Perspectives

13:30 - 15:00, David M. Karl, Chair

Karl Banse: Rates of Phytoplankton Growth.

Gregory Mitchell: Light Limitation in the Southern Ocean.

Kenneth Bruland: Potential Interactions Between Bioactive Trace Metals and Plankton.

Panel Discussion: Evaluating the Evidence on Smaller Scales

15:15 - 17:15, Patricia A. Wheeler, Chair

Contributing Panelists:

Alison Butler
Richard C. Dugdale
George A. Jackson
Neil M. Price
John Rueter
Dorothy G. Swift

Posters

18:00 - 21:00

DAY 3, SUN, FEB. 24

Fertilizing Nutrient-Rich Seas: Considerations and Consequences

08:30 - 10:00, James J. McCarthy, Chair

Jorge L. Sarmiento: Model Estimates of Potential Enhancement of Oceanic CO_2 Uptake by Iron Fertilization of the Southern Ocean.

Tsung-Hung Peng and W. Broecker: Uptake of CO_2 by an Iron-Fertilized Region of the Southern Ocean.

Wolfgang H. Berger: Antarctic Productivity, a Geologic Perspective.

Panel Discussion: Larger-Scale Processes

10:20 - 12:00, Thomas M. Powell, Chair

Contributing Panelists:

Osmund Holm-Hansen
Michael Pilson
Thomas M. Powell
Walker O. Smith

Open Forum: A Search for Consensus (or Majority and Minority Opinions)

13:30 - 15:00, James J. Morgan, Chair

Present state of our understanding
Critical uncertainties
Experimental Design
Course of Action, including consideration of a pilot experiment

POSTER PRESENTATIONS

Abbott, Mark: CZCS Observations of Phytoplankton Pigment in the Southern Ocean.
Ahmed, S.I., F. Azam and D.C. Smith: The Role of the Microbial Foodweb in Iron Regulation of the Carbon Pump.
Baum, Eric: A Model for the Upper Ocean Mixed Layer Environment.
Brand, Larry: How Much Iron do Oceanic Phytoplankton Need?
Butler, Alison: Iron Acquisition by Marine Bacteria: Novel Siderophores.
Chavez, Fransisco: Equatorial Pacific Microbial Food Webs in Relation to Iron.
Coale, Kenneth H: Effects of Iron, Manganese, Copper, and Zinc Enrichments on Productivity and Biomass in the Subarctic Pacific.
De Baar, Hein: Distribution of Dissolved Cadmium, Copper and Iron in the Weddell and Scotia Seas.
Fiedler, Paul & N. Philbrick: Upwelling and Productivity Along Zonal Divergences in the Eastern Tropical Pacific.
Fish, William: Use of Ferrodoxin as an Indicator of Iron Stress in Phytoplankton.
Gottlieb, Peter and R. Gorecki: An Ecosystem Model of Phytoplankton Limitation.
Guildford, Stephanie J: The Application of Phytoplankton Nutrient Status Indicators in Freshwater and Marine Environments.
Hudson, Robert: Complexation Kinetics, Diffusion and Phytoplankton Iron Uptake Mechanisms.
Hall, Julie: Perennially Low Biomass in a Nutrient-Rich Coastal Upwelling System.
Iverson, Richard L: The Relation Between Phytoplankton Carbon Production and Nitrogen New Production in Marine Environments.
Jackson, George A: Control of Phytoplankton Biomass During Blooms by Coagulation Processes.
Keller, Maureen D: DMS Production and Marine Phytoplankton: The Importance of Species Composition and Implications for a Changing Ocean System.
Kirchman, David L: Control of Bacterial Growth in the Subarctic Pacific, Station Papa.
Michaels, Anthony: Community Structure, Particle Export and Iron: Biological assumptions and Geochemical Implications.
Miller, William L: Studies of the Photochemical Cycling of Iron and its Role in Phytoplankton Growth.
Neale, Patrick: Does Vertical Mixing Enhance Diatom Growth Rates in Optically Deep Surface Layers?: Evidence from Long Time-Series in the English Lakes.
Orr, James: Oxygen Depletion as a Result of Iron Fertilization in a 3-D Ocean Model.
O'Sullivan, Daniel W., A.K. Hanson and D.R. Kester: The Distribution and Redox Chemistry of Fe(II) in Equatorial Pacific Surface Seawater.
Richardson, Laurie L: Phytoplankton Mediation of Manganese Cycling.
Rueter, John: Iron Content and Biochemical Efficiencies for Organisms Crucial to the Nitrogen Cycle.
Sherr, Evelyn B: Evaluation of Protistan Herbivory Using Fluorescently Labeled Algae.
Sulzberger, Barbara: Case Study on the Photoredox Cycling of Iron in Aquatic Systems.
Sullivan, Cornelius W: Chlorophyll a Standing Crops and Primary Productivity Rates in Antarctic Sea Ice.
Sunda, William G: Mutual Feedback Interactions Between Dissolved Zinc and Iron and Growth of Marine Phytoplankton.
Swift, Dorothy, W.G. Sunda & S.A. Huntsman: Oceanic Phytoplankton Need Less Iron.
Thomas, William H: Anomalous Nutrient-Chlorophyll Interrelationships in the Eastern Tropical Pacific Ocean.
Tindale, Neil & J. Yoder: Effect of Atmospheric Iron Addition on Shipboard Enrichment Experiments.
Unsworth, Nancy & J. Rueter: Iron Limitation Effects and Nitrogen Metabolism of *Synechococcus*.
Vernet, Maria: Phytoplankton Growth Rates During an Antarctic Spring Bloom.
Watson, Andrew: Proposal for a Small Scale In-Situ Fertilization Experiment.
Wells, Mark: What Fraction of Total Iron in Seawater is Available to Phytoplankton?
Wilkerson, F. and R. Dugdale: New Production in the Southern Ocean: Iron limited, Grazed or Cold-Adapted?
Yang, Sung R., R.M. Kudela and R.C. Dugdale: Control of New Production in the Pacific Equatorial Upwelling System: Experiments and Measurements with ^{15}N and Fe.

PARTICIPANT LIST

Abbott, Mark
College of Oceanography
Oregon State University
Corvallis, OR 97331-5503
Phone 503-737-4045; Fax 503-737-2064

Anderson, Donald M.
Biology Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone 508-547-2000 x 2351; Fax 508-457-2195

Azam, Farooq
Marine Biology Research Division, 0202
Scripps Institution of Oceanography/UCSD
University of California
La Jolla, CA 92093-0202
Phone 619-534-6850

Banse, Karl
School of Oceanography, WB-10
University of Washington
Seattle, WA 98195
Phone 206-543-5079; Fax 206-543-6073

Baker, Karen
Marine Research Division, 0218
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0218
phone 619-534-2350; Fax 619-534-5306

Barber, Richard T.
Duke University Marine Laboratory
Beaufort, NC 28516
Phone 919-728-2111; Fax 919-728-2514

Baum, Eric
TRW Bldg R1/1016
1 Space Park
Redondo Beach, CA 90278
Phone 213-812-0460

Benemann, John R.
Lawrence Berkeley Laboratory, Bldg. 70,
Room 126
Berkeley, CA 94720
Phone 415-724-4251; Fax 415-724-5282

Berger, Wolfgang H.
Geology Research Division, 0215
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0215
Phone, 619-534-2750; Fax 619-534-0784

Bidigare, Robert R.
Department of Oceanography
University of Hawaii
1000 Pope Rd.
Honolulu, HI 96822
Phone, 808-956-6567; Fax 808-956-9516

Brand, Larry
University of Miami, RSMAS
4600 Rickenbacker Cswy.
Miami, FL 33149
Phone, 305-361-4138; Fax 305-361-4106

Bruland, Ken
Marine Sciences
University of California, Santa Cruz
Santa Cruz, CA 95064
Phone, 408-459-4587; Fax 408-429-0146

Buck, Kurt
Monterey Bay Aquarium Research Institute
160 Central Ave.
Pacific Grove, CA 93950
Phone, 408-647-3747; Fax 408-649-8587

Buma, Anita G. J.
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg (Texel)
NETHERLANDS
Phone 31-2220-69465; Fax 31-2220-19674

Butler, Alison
Department of Chemistry
University of California, Santa Barbara
Santa Barbara, CA 93106
Phone 805-893-8178; Fax 805-893-4120

Caspi, Ron
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92092-0208
Phone 619-534-0638

Chadd, Helen
Department of Biological Sciences
University of Warwick
Coventry CV4 7AL
ENGLAND
Phone 0203-523523 X 2572; Fax 0203-523701

Chavez, Francisco
Monterey Bay Aquarium Research Institute
160 Central Ave.
Pacific Grove, CA 93950
Phone, 408-647-3709; Fax 408-649-8587

Chisholm, Sallie W.
Massachusetts Institute of Technology, 48-425
Cambridge, MA 02139
Phone 617-253-1771

Coale, Kenneth H.
Moss Landing Marine Laboratories
P.O. Box 450
Moss Landing, CA 95039-0850
Phone 408-755-8671; Fax 408-753-2826

Cole, Raelyn
School of Oceanography, WB-10
University of Washington
Seattle, WA 98195
Phone 206-543-8655

Cochlan, William
Marine Biology Research Division, 0202
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202
Phone 619-534-3196

Cullen, John
Bigelow Laboratory for Ocean Sciences
McKown Point
W. Boothbay Harbor, ME 04575
Phone 207-633-2173

Dagg, Michael
Lumcon
8124 Highway 56
Chauvin, LA 70344
Phone 504-851-2801; Fax 504-851-2874

Davies, Anthony G.
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM
Phone 44-752-222772
Fax 752-670637

De Baar, Hein J. W.
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg (Texel)
NETHERLANDS
Phone 31-2220-69465; Fax 31-2220-19674

DiTullio, Giacomo (Jack)
Moss Landing Marine Laboratories
Moss Landing, CA 95039
Phone 408-755-8671

Doucette, Greg
Biology Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone 508-548-1400 x2584; Fax 508-457-2195

Downs, Jan Newton
Monterey Bay Aquarium Research Institute
160 Central Ave.
Pacific Grove, CA 93950
Phone 408-647-3745; Fax 408-649-8587

Duce, Robert A.
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882
Phone 401-792-6222; Fax 401-792-6889

Dugdale, Richard C.
Department of Biological Sciences
University of Southern California
University Park, Los Angeles, CA 90089-0371
Phone 213-740-5132

Dusenberry, Jeffrey A.
Massachusetts Institute of Technology, 48-208
77 Massachusetts Ave.
Cambridge, MA 02139
phone 617-253-1969; Fax 617-258-8850

Erel, Yigal
Division of Geological and Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Falkowski, Paul
OASD
Brookhaven National Laboratory
Upton, NY 11973
Phone 516-282-2961; Fax 516-282-2060

Fee, James A.
Mail Stop C-345
Los Alamos National Laboratory
Los Alamos, NM 87545
Phone 505-667-0774, Fax 505-665-3166

Fiedler, Paul
NOAA/NMFS/SWFSC
P.O. Box 271
La Jolla, CA 92038
Phone 619-546-7016; Fax 619-546-7003

Fish, William
Oregon Graduate Institute
19600 NW Von Neumann Dr.
Beaverton, OR 97006-1999
Phone 503-690-1099; Fax 503-690-1273

Fitzwater, Steve
P.O. Box 450
Moss Landing Marine Laboratories
Moss Landing, CA 95039
Phone 408-755-8667; Fax 408-753-2826

Frost, Bruce W.
School of Oceanography WB-10
University of Washington
Seattle, WA 98195
Phone 206-543-7186; Fax 206-543-6073

Fuhrman, Jed
Department of Biological Science
University Southern California
Los Angeles, CA 90089-0371
Phone 213-740-5757 or 5759; Fax 213-740-8123

Fujita, Rodney M.
Environmental Defense Fund
257 Park Avenue South
New York, NY 10010
Phone 212-505-2100; Fax 212-50[illegible]75

Gargett, Ann
Institute of Ocean Science
P.O. Box 6000
Sidney, B.C. V8L 4B2
CANADA
Phone 604-363-6554; Fax 604-363-6746

Geider, Richard
University of Delaware
Lewes, DE 19958
Phone 516-282-2903

Goldman, Charles R.
Division of Environmental Studies
University of California, Davis
Davis, CA 95616
Phone 916-752-1557 or 3026; Fax 916-752-3350

Gordon, Michael
Moss Landing Marine Laboratory
P.O. Box 450
Moss Landing, CA 95039

Gorecki, Ricardo
TRW Bldg. 01/Rm 2251
One Space Park
Redondo Beach, CA 90278
Phone 213-813-9384; Fax 213-812-7933

Gottlieb, Peter
TRW Space & Technology Group, RI-2144
One Space Park
Redondo Beach, CA 90278
Phone 213-812-0282 ; Fax 213-812-1363

Granéli, Edna
Department of Marine Ecology
Lund University
Box 124
S-22100 Lund
SWEDEN
Phone 46-46-152984; Fax 46-46-146030

Greene, Richard
Oceanographic Sciences Division
Brookhaven National Laboratory
Upton, NY 11973
Phone 516-282-5982; Fax 516-282-2060

Guildford, Stephanie J.
Freshwater Institute
501 University Crescent
Winnipeg, Manitoba
CANADA R3T 2N6
Phone 204-983-5225; Fax 204-983-6285

Hall, Julie
Taupo Research Laboratory
DSIR Marine & Freshwater
P.O. Box 415
Taupo
NEW ZEALAND
Phone 63-69099 ext. 7545; Fax 63-505-623

Hanson, Alfred K.
Graduate School of Oceanography
University of Rhode Island
South Ferry Rd.
Narragansett, RI 02882-1197
Phone 401-792-6527; Fax 401-792-6818

Hanson, Roger B.
Division of Polar Programs, Room 611
National Science Foundation
Washington, D.C. 20550
Phone 202-357-7894; Fax 202-357-9422

Haygood, Margo
Marine Biology Research Division, 0202
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202
Phone 619-534-5987; Fax 619-534-7313

Hayward, Thomas L.
Marine Life Research Group, 0227
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0227
Phone 619-534-4479

Hoffman, Michael R.
W.M. Keck Laboratories
California Institute of Technology
Pasadena, CA 91125

Holm-Hansen, Osmund
Marine Biology Building, 0202
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202
Phone 619-534-2339; Fax 619-534-7313

Hudson, Robert
Tetra Tech Inc.
2 Bay Rd.
Hadley, MA 01035
Phone 413-586-8645; Fax 413-586-9462

Hutchins, David A.
273 Applied Sciences
University of California, Santa Cruz
Santa Cruz, CA 95064
Phone 408-459-2682

Iverson, Richard L.
Department of Oceanography
Florida State University
Tallahassee, FL 32306
Phone 904-644-1730 or 6700; Fax 904-644-2581

Jackson, George A.
Department of Oceanography
Texas A&M University
College Station, TX 77843
Phone 409-845-0405; Fax 409-845-6331

Jassby, Alan D.
Division of Environmental Studies
University of California, Davis
Davis, CA 95616
Phone 916-752-3938 or 3026; Fax 916-752-3350

Karl, David M.
School of Ocean and Earth Science
and Technology
University of Hawaii
Honolulu, HI 96822
Phone 808-956-8964; Fax 808-956-9516

Keller, Maureen D.
Bigelow Laboratory for Ocean Sciences
McKown Point
West Boothbay Harbor, ME 04575
Phone 207-633-2173; Fax 207-633-6584

Kirchman, David L.
College of Marine Studies
University of Delaware
Lewes, DE 19958
Phone 302-645-4375; Fax 302-645-4028

Kudela, Raphael
Department of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0371
Phone 213-740-5147; Fax 213-740-8123

Kunzig, Robert
Discover Magazine
3 Park Avenue
New York, NY 10016
Phone 212-779-6617; Fax 212-725-3962

Lee, Cindy
Marine Sciences Research Center
SUNY, Stony Brook
Stony Brook, NY 11794
Phone 516-632-8741; Fax 516-632-8820

Lehman, John T.
Department of Biology
Natural Science Bldg.
University of Michigan
Ann Arbor, MI 48109
Phone 313-763-4680; Fax 313-747-0884

Lesser, Michael P.
Bigelow Laboratory for Ocean Sciences
McKown Point
West Boothbay Harbor, ME 04575
Phone 207-633-2173; Fax 207-633-6584

Lloyd, Philippa
Nature
4 Little Essex St.
London WC2R 3LF
UNITED KINGDOM
Phone 71-836-6633 x2238; Fax 71 836-9934

Longhurst, Alan
Biological Oceanography Division
Bedford Institute Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
CANADA B2Y 4A2
Phone 902-426-3886

Marrs, Barry
Du Pont
Central Res. & Dev. Exp. Station
P.O. Box 80173
Wilmington, DE 19880
Phone 302-695-3933; Fax 302-695-9183

Martin, John H.
Moss Landing Marine Laboratory
P.O. Box 450
Moss Landing, CA 95039
Phone 408-755-8655; Fax 408-753-2826

Mayer, Larry
Department of Oceanography
University of Maine
Walpole, ME 04573
Phone 207-563-3146

McCarthy, James
Museum of Comparative Zoology
Harvard University
Cambridge, MA 02138
Phone 617-495-2330

McKnight, Diane
5293 Ward Road
USGS-WRD
MS 408
Arvada, CO 80002
Phone 303-236-3611; Fax 303-467-9598

McQuoid, Melissa
Department of Biology
Whitman College
Walla Walla, WA 99362

Michaels, Anthony F.
Bermuda Biological Station for Research, Inc.
17 Biological Lane
Ferry Reach, GE01
BERMUDA
Phone 809-297-1880; Fax 809-297-8143

Miller, Charles B.
College of Oceanography, Bldg. 104
Oregon State University
Corvallis, OR 97331-5503
Phone 503-757-9627; Fax 503-737-2064

Miller, William L.
Graduate School of Oceanography
University of Rhode Island
South Ferry Rd.
Narrangansett, RI 02882-1197
Phone 401-792-6625; Fax 401-792-6818

Minas, Hans J.
Université d'Aix Marseille 2
Centre D'Océanologie de Marseille
Faculté des Sciences de LUMINY
13288 Marseille Cedex 9
FRANCE
Phone 91-26-91-05; Fax 91-26-92-99

Mitchell, Greg
NASA HQ
Code SEP
Washington, D.C. 20546
Phone 202-453-1720; Fax 202-755-2552

Morel, Francois M. M.
Massachusetts Institute of Technology, 48-423
Cambridge, MA 02139
Phone 617-253-3726; Fax 617-258-8850

Morgan, James J.
California Institute of Technology, 138-78
Pasadena, CA 91125
Phone 818-356-4394; Fax 818-356-2940

Najjar, Raymond
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307-3000
Phone 303-497-1627; fax 303-496-1137

Neale, Patrick
Department of Plant Biology, 111 G.P.B.B.
University of California, Berkeley
Berkeley, CA 94720
Phone 415-642-6209; Fax 415-642-4995

Nelson, David M.
College of Oceanography
Oregon State University
Corvallis, OR 97331-5503
Phone 503-737-3962 ; Fax 503-737-2064

O'Sullivan, Daniel W.
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882-1197
Phone 401-792-6625; Fax 401-792-6818

Olson, Robert J.
Biology Department
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone 508-457-2000 x2565; Fax 508-457-2195

Orr, James
AOS Program
Princeton University
Princeton, NJ 08544-0710
Phone 609-258-1312; Fax 609-258-2850

Paytan, Adina
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0008
Phone 619-534-6302

Peng, Tsung-Hung
Environmental Science Division
Oak Ridge National Laboratory
Bldg. 1000, MS-6335
Oak Ridge, TN 37831-6335
Phone 615-574-0390; Fax 615-574-2232

Philbrick, Valerie
NOAA/NMFS/SWFSC
P.O. Box 271
La Jolla, CA 92038
Phone 619-546-7166; Fax 619-546-7003

Pilson, Michael
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882-1197
Phone 401-792-6104; Fax 401-792-6160

Pinza, Meg
Battelle Marine Science Laboratory
Sequim, WA 98382

Pomeroy, Lawrence
Institute of Ecology
University of Georgia
Athens, GA 30602
Phone 404-542-3415; Fax 404-542-6040

Powell, Thomas M.
Division of Environmental Studies
University of California, Davis
Davis, CA 95616
Phone 916-752-1180 or 3026; Fax 916-752-3350

Prézelin, Barbara B.
Department of Biological Sciences
University of California, Santa Barbara
Santa Barbara, CA 93103
Phone 805-893-2879; Fax 805-893-4724

Price, Neil M.
Massachusetts Institute of Technology, 48-213
Cambridge, MA 02139
Phone 617-253-1936

Raven, John A.
Department of Biological Sciences
University of Dundee
Dundee, DD1 4HN
UNITED KINGDOM
Phone 44-382-307281; Fax 44-382-22318

Reeve, Michael R.
Ocean Sciences Division, Room 609
National Science Foundation
Washington, D.C. 20550
Phone 202-357-9600; Fax 202-357-7621

Reynolds, Rick
Department of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0371
Phone 213-740-5813

Richardson, Laurie L.
Department of Biological Sciences
Florida International University
Miami, FL 33199
Phone 305-348-1988; Fax 305-348-1986

Ringold, Paul
U.S. Environmental Protection Agency, RD-682
401 M St. SW
Washington D.C. 20460
Phone 202-382-5609; Fax 202-382-6370

Rueter, John
Department of Biology
Portland State University
P.O. Box 751
Portland, OR 97207
Phone 503-725-3194; Fax 503-725-3864

Sanchez, Lionel
O&M Building
Texas A&M University
College Station, TX 77843
Phone 409-845-2597; Fax 409-845-6331

Sandgren, Craig D.
Department of Biological Sciences
University of Wisconsin-Milwaukee
Milwaukee, WI 53201
Phone 414-229-4779; Fax 414-229-3926

Sarmiento, Jorge L.
AOS Program
Princeton University
P.O. Box CN710
Princeton, NJ 08544-0710
Phone 609-258-6585; Fax 609-258-2850

Shapiro, Joseph
Limnological Research Center
University of Minnesota
220 Pillsbury Hall
Minneapolis, MN 55455
Phone 612-624-0596; Fax 612-625-3819

Shapiro, Lynda
Institute of Marine Biology
University of Oregon
Charleston, OR 97420
Phone 503-888-2581; Fax 503-888-3250

Sherr, Evelyn B.
College of Oceanography,
Oceanogr. Admin. Bldg. 104
Oregon State University
Corvallis, OR 97331-5503
Phone 503-737-4369; Fax 503-737-2064

Shuford, Robert B.E. III
Belle W. Baruch Institute, Box 21
University of South Carolina
Columbia, SC 29208
Phone 803-777-2390 or 3938

Smayda, Ted
Graduate School of Oceanography
University of Rhode Island
Kingston, RI 02881
Phone 401-792-6171; Fax 401-792-6160

Smith, David C.
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202
Phone 619-534-3196; Fax 619-534-7313

Smith, Walker O.
Graduate Program in Ecology
University of Tennessee
Knoxville, TN 37996
Phone 615-974-3065; Fax 615-974-4007

Stockwell, Dean
Marine Science Institute
University of Texas at Austin
P.O. Box 1267
Port Aransas, TX 78373-1267
Phone 512-749-6705

Sullivan, Cornelius W.
Department of Biological Science
University of Southern California
Los Angeles, CA 90089-0371
Phone 213-740-5805

Sulzberger, Barbara
Institute of Water Resources and
Water Pollution Control
CH-8600 Dübendorf
SWITZERLAND
Phone 01-823-50-96; Fax 01-823-50-28

Sunda, William G.
Oceanic Chemistry Program, Code 1123C
Office of Naval Research
800 N. Quincey St.
Arlington, VA 22217-5000
Phone 703-696-4591; Fax 703-696-3945

Suttle, Curtis
Marine Science Institute
University of Texas
P.O. Box 1267
Port Aransas, TX 78373-1267
Phone 512-749-6733; Fax 512-749-6777

Swift, Dorothy G.
Graduate School of Oceanography
University of Rhode Island
South Ferry Rd.
Narragansett, RI 02882
Phone 401-792-6765; Fax 401-792-6898

Taylor, Dennis L.
Bigelow Laboratory for Ocean Sciences
West Boothbay Harbor, ME 04575
Phone 207-633-2173; Fax 207-633-6584

Tebo, Brad
Marine Biology Research Division, 0202
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202
Phone 619-534-5470; Fax 619-534-7313

Thomas, William H.
Marine Research Division, 0218
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0218
Phone 619-534-2211

Timmermans, Klaas R.
Netherlands Institute for Sea Research
P.O. Box 59
1790 AB Den Burg (Texel)
NETHERLANDS
Phone 31-2220-69465; Fax 31-2220-19674

Tindale, Dr. Neil
University of Rhode Island
Narragansett, RI 02882-1197
Phone 401-792-6756; Fax 401-792-6898

Trees, Charles C.
CHORS
San Diego State University
6505 Alvarado Rd. #206
San Diego, CA 92120-5005
Phone 619-594-2241; Fax 619-592-4570

Trick, Charles
Department of Plant Sciences
University of Western Ontario
London, Ontario
CANADA N6A 5B7
Phone 519-661-3899; Fax 519-661-3935

Unsworth, Nancy
Department of Biology
Portland State University
P.O. Box 751
Portland, OR 97207
Phone 503-725-3194; Fax 503-725-3864

Valdsaar, Herbert
E. I. Du Pont de Nemours & Co. , Inc.
Jackson Laboratory
Deepwater, NJ 08023
Phone 609-540-3057; Fax 609-540-4530

Vallino, Joe
Marine Biology Building, 0202
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0202

Vernet, Maria
Marine Research Division, 0218
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92093-0218
Phone 619-534-5322; Fax 619-534-5306

Waite, T. David
Environmental Science Program
Australian Nuclear Science &
Technology Organization
Private Mail Bag 1
Menai, NSW 2234
AUSTRALIA
Phone 011-61-2-543-3896;
Fax 011-61-2-543-9260

Walker, Henry A.
U. S. Environmental Protection Agency
Environmental Research Laboratory
27 Tarzwell Dr.
Narragansett, RI 02882
Phone 401-782-3134; Fax 401-782-3030

Wassmann, Paul
Norwegian College of Fishery Science
University of Tromsø
N-9000 Tromsø
NORWAY
Phone 47-83-44000; Fax 47-83-71832

Watson, Andrew
Plymouth Marine Laboratory
Prospect Place
West Hoe, Plymouth PL1 3DH
UNITED KINGDOM
Phone 44-752-222772; Fax 44-752-670637

Weiler, C. Susan
Department of Biology
Whitman College
Walla Walla, WA 99362
Phone 509-527-5948; Fax 509-527-5961

Wells, Mark
Marine Research Division, 0220
Scripps Institution of Oceanography/UCSD
La Jolla, CA 92037-0220
Phone 619-534-2108; Fax 619-534-0784

Wheeler, Patricia A.
College of Oceanography
Oregon State University
Corvallis, OR 97331
Phone 503-737-0558; Fax 503-737-2064

Wilkerson, Frances
Department of Biological Science
University of Southern California
University Park
Los Angeles, CA 90089-0371
Phone 213-740-5132

Williams, Peter J. Le B.
School of Ocean Sciences
University College of North Wales
Menai Bridge
Gwynedd, LL59 5EH
UNITED KINGDOM
Phone 248-351151 ext. 2840; Fax 248-716-367

Yang, Sung R.
Department of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0371
Phone 213-740-5133; Fax 213-740-8123

Yoder, Jim
Graduate School of Oceanography
University of Rhode Island
South Ferry Rd.
Narragansett, RI 02881
Phone 401-792-6864; Fax 401-792-6728

Zika, Rod
RSMAS
University of Miami
4600 Rickenbacker Cswy.
Miami, FL 33149
Phone 305-361-4715